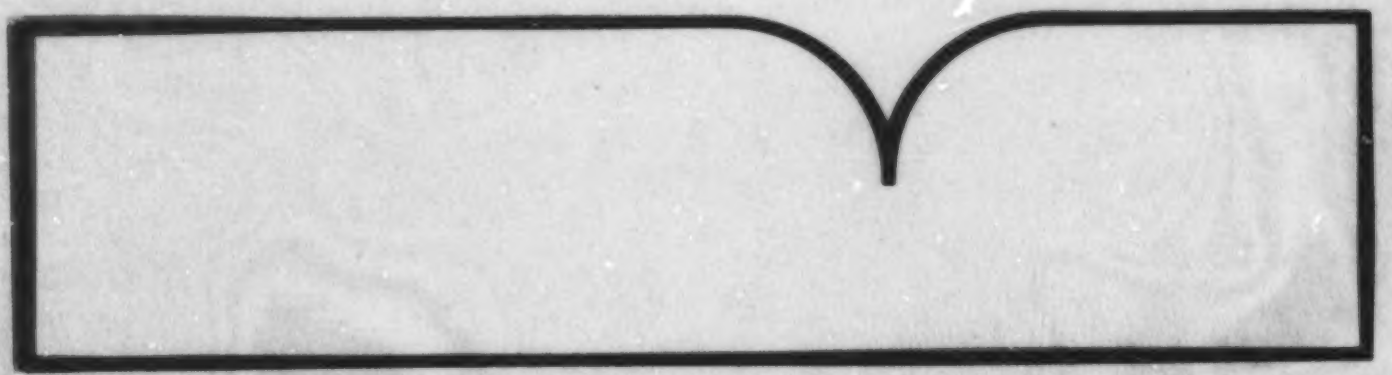
PB87-102521

Integration of Monitoring and Research in Coastal Waters: Issues for Consideration from a Regulatory Point of View

(U.S.) Environmental Research Lab.
Gulf Breeze, FL

Sep 86



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1. REPORT NO.	2.	3. RE PB87-102521
EPA/600/D-86/214		

4. TITLE AND SUBTITLE
INTEGRATION OF MONITORING AND RESEARCH IN COASTAL WATERS: Issues for Consideration from a Regulatory Point of View

5. REPORT DATE
September 1986

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
same as #12

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Gulf Breeze, FL 32561

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE
EPA/600/04

15. SUPPLEMENTARY NOTES

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	14
	20. SECURITY CLASS *(This page)*	22. PRICE
	UNCLASSIFIED	

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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INTEGRATION OF MONITORING AND RESEARCH IN COASTAL WATERS: ISSUES FOR CONSIDERATION FROM A REGULATORY POINT OF VIEW

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ABSTRACT

Coastal marine ecosystems are characterized by a high degree of natural variability. The weak resolving power of marine science to differentiate between effects ascribable to natural factors versus human intervention often leads to unrealistic expectations of "goods and services" that these ecosystems can provide. This high uncertainty often contributes to faulty communication among scientists, resource managers and the public. We believe that this problem is further enhanced by misunderstandings of the need to intergrate monitoring and research. We explain why monitoring is a retrospective activity and the principal way it can become a prospective activity is through hypothesis framing, testing, and modeling.

We describe the logic that underpins a program designed to characterize the limits of applicability of extrapolation from laboratory data to the field. This interactive, iterative process couples concepts of monitoring and research so that the research question and method are linked to spatial and temporal scales of ecological variability. Without such considerations, important ecological relationships remain unspecified, thus precluding meaningful approaches to management of such complex but valuable ecosystems.

1. INTRODUCTION

Most coastal waters, especially estuaries, are ecologically complex, variable, and highly valued for their environmental amenities and resources. It is our intention to discuss how integration of research and monitoring activities can apply to continuing problems of serious environmental degradation in many of these systems.

Need for this integration is widely acknowledged by environmental scientists and resource managers. Our experience suggests that a disparity exists in how environmental monitoring and research in coastal waters are coordinated and integrated versus the existing knowledge of how to harmonize these two activities to better serve the mutual interest of management and science. This is especially true for environmental assessments (1-2).

Our thesis is that monitoring and research have become significantly decoupled during the past few decades, especially in pollution studies of coastal marine ecosystems. Decoupling has resulted in an important weakening of the cause and effect resolving power of coastal marine science. In a related commentary with emphasis on freshwaters, Likens (3) argued for more meaningful long-term monitoring which would provide the basis for framing testable hypotheses. He contended that "innovative research (and thinking) which is based on long-term empirical data is critical to the development and maturation of ecology, and is fundamental to the establishment of high-quality resource management programs."

At the scale of an estuary or a major segment thereof, one usually discovers only loose associations between contaminant residues and associated effects with patterns of industrialization and urbanization around the coasts, although some new approaches to statistical modeling are quantifying some of these relationships (4). With regard to monitoring data, recent emphasis in coastal waters has been on interpretation of historical trend data involving such variables as freshwater flows, tides, temperature, salinity, dissolved oxygen and biota (5). There is evidence that, when monitoring and research are integrated, significant progress can be made in evaluating the importance of toxic chemical and other effects on marine life at the population, community and ecosystem levels of organization (6-10).

Monitoring, regardless of specific objectives, i.e., baseline surveys, trend monitoring, impact detection, compliance monitoring, establishment of causality and predictions, has the general purpose of determining whether an environment is or will be changed from its reference state by anthropogenic or non-anthropogenic causes (11). Monitoring tracks important changes that occur in the ecosystem of interest and helps to define relationships that warrant application of functionally oriented research (12). Whether conducted in the laboratory or field, research is a key analytical approach to understanding ecological complexities and establishing causal relationships. Thus, in an applied context, monitoring and research are seen as

complementary ways of gaining useful knowledge about estuarine ecosystems. Comparative estuarine science helps make this knowledge more generalizable; hence, of greater utility (13).

In a strict sense, there are situations that do not lend themselves readily to the more traditional concept of integrating monitoring and research. For example, environmental degradation may occur so rapidly that resource managers must act immediately despite numerous scientific uncertainties. In such situations, one can perform initial "desk analyses" based on existing information and attempt to provide useful scientific guidance. It may be feasible to carry out a so-called management experiment, whereby a structured monitoring effort that utilizes hypothesis testing is designed to evaluate success of a regulatory or management action (1[illegible]14). This, of course, typically lacks the analytical control of more structured field and laboratory experimental research.

As background, we discuss under the title of observations some general features of what is well-known and not well-known about estuaries and contaminants. We next address some impediments to progress by examining factors other than technical and conceptual design features required to integrate monitoring and research effectively. Our rationale for including the topic of impediments in a largely conceptual discussion is based on experience that suggests that applied science is not conducted in a regulatory or resource management vacuum. A discussion is provided of the importance of understanding temporal and spatial scales of ecological processes. Then, we examine a hierarchically structured approach to integrate monitoring and research that provides a basis for defining the limits of field extrapolation of laboratory-derived information to the coastal marine environment.

2. OBSERVATIONS

Comments on What Is Well-known

In the United States, the majority of the human population resides in the coastal zone, and the numbers of people are expected to continue to increase, especially in the coastal zone of the "sunbelt" states (15). Based on the observation that many coastal marine ecosystems, especially estuaries, are still experiencing environmental degradation, there is a need to improve our scientific understanding and predictability for management purposes.

The term estuary is a descriptor that covers a wide range of physical types of systems and, in the aggregate, these systems are characterized by a diverse biota and multiple uses. These systems are a demanding environment as illustrated by the lower species diversity between marine and freshwaters (16). Estuaries are ecologically complex and variable in their populations, chemical properties (e.g., salinity, ionic constitency, dissolved oxygen concentrations, etc.), temperature, anthropogenically-derived contaminants and physical driving forces (e.g., tides, sunlight, and freshwater inputs).

Most estuaries receive a complex mix of contaminants that includes sediments, nutrients, trace metals and toxic organic chemicals from point and non-point sources. Since about 1880, there has been a significant increase in the use of inorganic fertilizers (17) that can be transported to coastal waters. Many estuaries received large supplies of trace metals during the industrial revolution and high concentrations are still found in the sediments.

Synthetic organic chemicals began to increase in coastal waters about the time of WW II. Some estimates suggest that about 70,000 chemicals are currently in commercial use and approximately 1,000 new ones are synthesized each year (8). The presence of many toxic organic chemicals in estuaries, some at very high concentrations, is confirmed by sediment and tissue analysis.

With regard to sediments, nutrients, and trace metals, many estuaries have received these materials for decades to centuries, (e.g., land clearing for agriculture in the Chesepeake Bay area significantly increased the supply of sediments to the upper Chesapeake and its tributaries by the mid-1700's) (18). We speculate that human intervention in many estuarine processes in the United States preceded the industrial revolution, and further research is required to assess the time and pattern of recovery of ecosystems subject to long-term environmental stress.

Relatively few, quantitative, long-term data sets document the presumed increase in mass loading of contaminants to tidal waters from land run-off or aerial deposition. Also, few studies have addressed mass balance for the load of a particular contaminant to coastal tidal waters. Ability to calculate mass balance is an important component for characterization of the fate of contaminants; fate being essential to relating biological effects to exposure concentrations (19).

Most knowledge concerning the effects of contaminants is based on laboratory studies, often on a limited number of species. However, in recent years, use of multispecies tests (microcosms and mesocosms) in studies of contaminant fate and effects has increased (20-24). Recycling of nutrients supports much of the primary production in estuarine ecosystems and the benthic compartment is very important in the recycling process. Trace metals also enter the biogeochemical cycle in these ecosystems; some knowledge is

available about total metal concentrations and their physical transport, but information on effects of the biologically active forms of metals is limited.

Local areas of many estuaries constitute a public health risk because of human pathogens, while some toxicants have been found to bioconcentrate and/or biomagnify to become known or potential risks to human consumers. But, the risk to marine populations that contain high tissue residues is less clearly understood, with the exception of some pesticides. Gross biological effects of certain materials contained in oil spills and outfalls are much better described.

Comments on What Is Not Well-Known

Our purpose is not to list a long set of definitive statements about what is unknown in a causal context. We believe that lack of predictive ability for estuaries is based on lack of in-depth knowledge of ecological processes and that this precludes understanding of how these ecosystems respond to the broad array of contaminants. Nixon (17) described a number of areas that lack scientific understanding, especially the effects of interaction between nutrient enrichment and toxic chemicals. Apparently, firm cause and effect relationships tend to be presumed, rather than demonstrated. In this respect, scientific uncertainty is still a major factor in coastal marine science. These uncertainties provide opportunities and challenges for estuarine science to respond to with a renewed sense of purpose. However, progress may require a more effective coupling of monitoring and research activities and incorporation of this concept in an overall coastal marine research strategy. For example, the recent scientific phase of the U.S. EPA Chesapeake Bay Program demonstrated the difficulty of evaluating variability of historical data derived from non-integrated monitoring and research (18).

Impediments to Progress: Uneasy Alliances

Effective management of pollution requires knowledge of detrimental effects that occur in the environment and the factors that cause those effects (25). Operationally, this requires an ability to distinguish variability associated with non-anthropogenic factors from human intervention. Many pollution problems in estuaries have a long history. Solutions have been compromised by scientific uncertainty, theoretical limitations, economic constraints, multiple use conflicts, and the changing nature in the variety of pollutants. To these constraints are added the different objectives of scientists and resource managers. Scientists tend to prefer to work in areas where uncertainties are high, and which provide opportunities for discovery, whereas the public and environmental managers tend to prefer more certainty about their environment and in their decisionmaking (26). Ruckelshaus (27) suggested that these opposing tendencies are the source of an uneasy alliance among scientists, regulators and managers. There is merit in this suggestion, but we also suggest that there are other examples of uneasy alliances that have major impacts on the manner in which coastal marine research is applied to managerial needs.

In addition to the budget cycle problem, research managers often emphasize short-term commitments and products and maintain a reward system that is biased in favor of scientifc productivity associated with short-term studies. Thus, hypotheses that have a relatively long-term component, e.g., 5 to 10 years, may not receive strong support. We believe that long-term monitoring and research can be organized constructively into important milestones that do not place unreasonable burdens on publication records. Long-term data have been generated through wisdom and tenacity by individuals and occasionally by institutions, and these data often become the "centerpiece" for problem analysis (e.g., the striped bass juvenile index developed by the State of Maryland for Chesapeake Bay) (18,28).

Of special concern are situations in which resource managers are confronted with serious environmental problems and scientists, in good faith, differ in their assessments. The Hudson River power plant controversy that failed to resolve, scientifically, the striped bass (Morone saxatilis) recruitment issue is an example. The issue pitted resource managers, scientists, industry officials and members of public interest groups against each other (29). Some resolution to such problems is possible if each proponent of an hypothesis points out reasonable alternative hypotheses and major uncertainties not addressed by research (30). Another uneasy alliance shows up in the need for intra- and interagency coordination. Some agencies or their subunits are responsible primarily for fisheries research, others for physical marine science, and others for water quality. Therefore, monitoring and research are often administratively separated and budgets defended independently. This overtaxes the ability of the most dilligent research manager to implement an inter-disciplinary ecological program within and among governmental agencies.

We have addressed some nontechnical issues that we feel impinge upon the success of our

nation's ability to maintain and improve its management of coastal resources. This brief treatment is intended to be indicative through selected examples, not comprehensive. As we look to the future (i.e., the year 2000), we should ask ourselves - Are we organized to detect at an early stage and make effective responses to generalized problems of deterioration of resources such as Chesapeake Bay?

This would likely require an improvement in predictive capabilities (coupling of research and monitoring) with regard to the ecological response of coastal ecosystems to present and future levels of environmental stress.

3. SCALE CONSIDERATIONS

An appreciation of scale is a critical feature in coupling field monitoring with field and laboratory research. The following quotation, though originally made in an oceanographic context, is applicable to coastal waters and estuaries:

> "In the past decade, a conceptual framework has emerged in the biological oceanographic community (31) in which the importance of understanding the variability of the marine ecosystem is accorded at least as much emphasis as quantification of the instantaneous or mean values of the system variables. It has also become recognized that ecosystem variance can occur simultaneously on more than one time-scale. Hand-in-hand with the evolution of these ideas has progressed the development of suitable instrumentation (32) and statistical tools (33) to describe the distribution or decomposition of variance in terms of temporal or spatial scale" (34).

It is difficult to explain why biological oceanography and coastal marine science have only recently accepted the importance of temporal and spatial scale in hypothesis formulation when it has been a working concept in physical oceanography (35), mathematical modeling (36) and other endeavors for years. For example, engineers would have great difficulty in building bridges if they did not appreciate scale and artists have appreciated the significance of spatial and temporal scales in their work for many years. Estuarine ecologists have recently begun to express their results in terms of time and space scales of variability of underlying processes (37).

Physical and biotic scaling was very important in design criteria in microcosm research in Narragansett Bay (22). Attention to scale enhanced the scientific meaning of a test of the hypothesis that ecosystems respond linearly to environmental fluctuations. This hypothesis was rejected as a generalization based on microcosm research (38).

The problem of scale as it relates to the bias created by experimental test systems, e.g., size of light and dark bottles in photosynthetic studies, is a well-known problem (39). Other questions concerning the importance of scale in plankton research (Figure 1) that are relevant to other components of the ecosystem are described by Harris (39) and Haury et al. (40). For example, it is important to understand relationships among physiological, ecological and climatic endpoints and how they relate to each other (e.g., see horizontal arrows in Figure 1). Steele (31) extends the concepts to higher trophic levels, including pelagic fishes. There are practical limits in experimental adjustments to scale and then the decision must be made whether to proceed with a research question.

A practical and readily understandable reason for our emphasis upon scale is the confounding effect of temporal and spatial scales on ecological variability. For example, in "red-tides" (dinoflagellates), the number of organisms contained in a sample may be determined by effects of several physical processes (i.e., Langmuir circulation, tidal fronts, upwelling), not to mention nutrient enrichment, biological grazing and differential responses of organisms to light gradients and diel cycles. Thus, making the simplistic assumption of homogeneity of the physical environment can lead to unexplained ecological variability which might otherwise be explained.

Early work on the scale of processes that explain the development of a dinoflagellate bloom showed that the growth rate had to overcome horizontal diffusive processes which tend to disperse the bloom (41). A patch size of less than 100 m in diameter would be dispersed rapidly by physical mixing. Later work increased the size to about 1.0 km, but considering the overall uncertainties, these estimates are surprisingly close (42). Tyler and Seliger (43) showed close coupling between physical transport processes, especially the estuarine counter-current, and seasonal timing of dinoflagellate blooms in Chesapeake Bay.

Linkage of long-term monitoring and research is being accomplished in Apalachicola Bay, Florida, and in the mouth of the York River estuary, Chesapeake Bay, Virginia (6). These studies draw on long-term (1972 to 1984) monitoring of benthic fishes, epibenthos

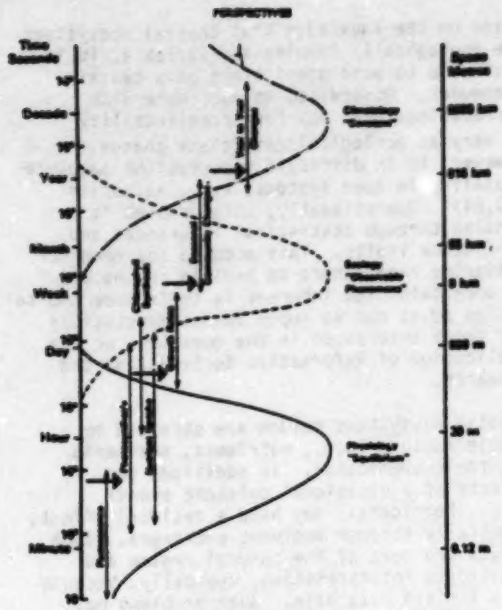

Figure 1. A summary of the hierarchy of the various algal resonses to the spectrum of environmental fluctuations. Temporal and spatial scales are linked by the processes of horizontal turbulent diffusion. The three bell curves roughly define the scales of interest to physiologists, ecologist, and climatologists. The horizontal arrows are meant to show that higher frequency (lower level) processes collapse into higher level responses. The figure does not pretend to be an exhaustive description. (From 39).

and infaunal macrobenthos in Apalachicola Bay, and about 7 years of data on benthic invertebrates in the lower York River estuary. Some important conclusions resulting from these studies are: 1) use of laboratory and field data to explain patterns observed in the field must be based on temporal and spatial variability of biological and non-biological components of the system in question; 2) thus, frequency of sampling is critical to the scale of variability of the measured endpoints; and 3) one must exercise care in relating the research question to the scale of ecological variability, otherwise false assumptions can lead to Dayton's (44) "mu" effect, which describes when the research question, sampling, and experimental design cannot be related meaningfully.

The issue of scale is a key factor in the formal definition of the term ecosystem (45,46). Lewis and Platt (34) addressed this issue -- and we paraphrase: The degree to which a particular area is said to be autonomous with respect to ecological dynamics is dependent on the size of the domain and the time scale over which autonomy is tested. They conclude that "autonomous systems are ecological units which can be specified by knowledge of the internal dynamics and the boundary conditions alone". The definition of the characteristic time scale for a given area is not a simple problem to match to the research question. In estuarine ecosystems, this theoretical view takes on practical importance because it is difficult to define the boundaries of ecological processes without a great deal of descriptive knowledge, much of which is derived from monitoring.

We believe that our concern about scale should be emphasized for those who design and implement monitoring, research and management programs for coastal marine environments. Interpretation of monitoring results is intimately associated with scale of measurement. The research community has many important questions to answer about scale effects, especially questions concerning how the extent of damage will change as a result of various remedial or disposal actions (47).

4. FIELD VALIDATION

General Considerations

The basic questions are old ones. What is required to predict environmental effects of a contaminant on a coastal ecosystem? How useful are laboratory studies, i.e., toxicity tests, in predicting effects on populations, communities and ecosystem processes? The water quality criteria published by the U.S. EPA (48) were based largely on single-species laboratory tests, yet results of these tests have been extrapolated to many field situations. The reason for asking questions in a broad context is that the concern may be at the organism- or population-level (e.g., decline of the snook fishery, Centropomus undecimalis, in southern Florida coastal waters), but the causal explanation may involve ecosystem-level processes.

Levin and Kimball (49) cite several reasons why it is difficult to extrapolate from laboratory to the field. For example, it is very difficult to simulate in laboratory test conditions that allow "normal" organismic behavior, the gradients of environmental factors tend to be steeper in testing apparatus (e.g., salinity in the field may change by 5 ppt over 10 km, but in a mesocosm, the same change may occur within a few meters). The variable spatial and temporal gradients in the field are difficult to duplicate.

It is practically impossible to test the effects of all contaminants over a wide range of field conditions. But, it is possible to identify common characteristics in the response of classes of contaminants to specific, dominant environmental variables (e.g., heavy metal speciation in various salinities as it relates to differential bioavailability). A more reasonable strategy would be to determine the predictive power of a laboratory test, or possibly a more complex analogue of field conditions (i.e., microcosm or mesocosm) to determine the reliability of extrapolation. Ideally, a series of tests of graded ecological complexity would allow a more refined analysis of the most accurate and predictive test system. In the process, one should be able to determine the simplest test system that performs within acceptable limits with a known degree of statistical confidence for a particular type of question.

The ability to perform an evaluation is enhanced by knowledge of ecological structure and function of the system, particularly its temporal and spatial scales of processes. "Otherwise, it is a giant step between test systems and the field" (50). This premise is based on factors other than the contaminant effects that are an important part of an ecological causal framework. Background information on life histories of key species is a necessary adjunct to understanding ecological relationships (51). The problem of using test systems to simulate the field is that the flow of information is directional (6). The field is the "reality" that is the object of predictability; test systems serve this objective. Insights gained from test systems may raise questions that would be of interest to examine in the field, but this interactive relationship does not change the overall objective.

A key point regarding laboratory and field test systems is that they often contain "artifacts" (6). It is a challenge to reduce the influence of this bias when relating the test system to the field. For example, it is often difficult to adjust for differential recruitment of organisms affected by structure of the test system or lack of refuge from predators where size of the test system prohibits adequate representation of such features. Obvious features, i.e., large schools of adult fish, are impossible to simulate in micro- or mesocosms. Therefore, field validation is limited in the kinds of questions that can be fully addressed through use of various sizes of container experiments. However, this limits, but does not invalidate its high utility in addressing other key questions (52).

Based on the knowledge that coastal ecosystems are ecologically complex and variable, it is desirable to base predictions on a causal framework. Otherwise, we must work with correlations that may lose predictability or vary as ecological conditions change. However, it is difficult to establish absolute causality in open systems, e.g., estuaries (53,54). Operationally, this problem is handled through statistical inferences and confidence limits. This adds to the need for estuarine researchers to explain the nature of uncertainities inherent in their experimental design so as not to imply false expectations for those interested in the questions or the application of information derived from the research.

Coastal ecosystems seldom are stressed by single factors (e.g., nutrients, sediments and toxic chemicals). In addition, the effects of a occasional episodic events (i.e., hurricanes) may have a residual effect, especially through sediment exchanges. Such events are part of the natural regime and complicate interpretation, typically, because of a limited data base. Such problems may complicate the location of reference areas. Mesocosms may help partially to off-set this difficulty (20).

The most elegant experimental design may focus on near-pristine areas as reference sites. Nutrient-enriched systems may respond differently to toxic chemical stress than nutrient-improvished ones (e.g., trace metal mobilization). This suggests that a more appropriate design would test toxic chemicals over a range of conditions that incorporate nutrient gradients. A further consideration is the extent that nutrient enrichment may affect the actual chemical exposure.

The Strategy

The previous discussion points out that it is often difficult to apply data from controlled laboratory single-species test systems to possible responses of estuarine systems, where almost limitless interactions occur at varying scales with characteristic frequencies, magnitude and duration. However, we believe that estuaries as ecosystems are neither totally chaotic nor totally deterministic; there is a basis for predictability. The problem is to focus on those interactions that contribute to variability important to the research question, not focus on all possible interactions.

Conceptual models are useful heuristic devices for focusing on relevant ecological interactions and provide a framework for research questions. Such models aid in identification of important

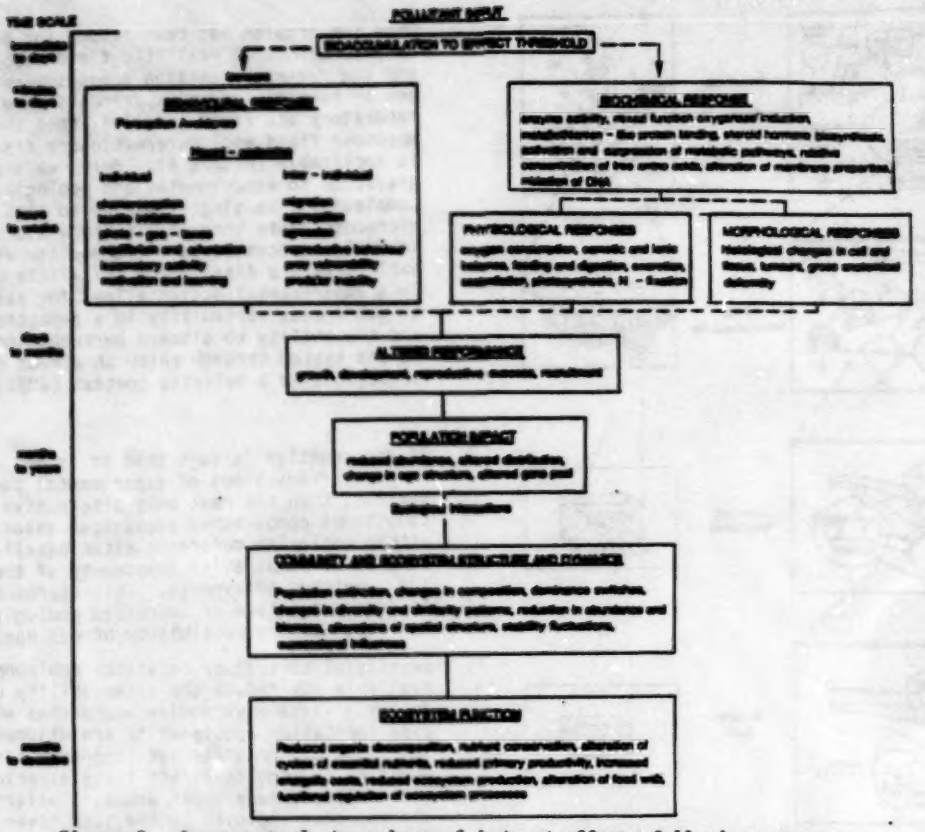

Figure 2. A conceptual chronology of induced effects following exposure to toxic pollutants, emphasing responses in individuals, populations, community and ecosystem structure and dynamics, and ecosystem function. (Modified from Sheehan, et al. (57).

parameters or endpoints used to measure biological and ecological variability (55, 56) and, most importantly, provide the rationale for hypothesis formulation.

Figure 2 is an example of a conceptual model that defines generally the chronology of induced effects of toxic chemicals for several levels of biological and ecological organization (57). In ecotoxicology, conceptual models serve to identify direct and indirect effects of contaminants as modified or masked by important environmental factors such as temperature, salinity, and dissolved oxygen and their combined interaction with ecosystem driving forces such as sunlight, tides, and wind effects on mixing of waters. Conceptual models are useful in simplifying ecosystem complexity (e.g., determining the configuration of population interactions and system parameters) (58).

Lethality is a widely used endpoint and has the unequivocal virtue of being final but does not offer much insight about the potentially more damaging effects of chronic stress. In general, induced toxic effects are observable in individuals before they are observed at higher levels of ecological organization (see Figure 2) (59,60,61). Early detection allows for corrective action based on presumptive evidence that population and ecosystem effects will occur. The challenge is to calibrate these early warning indicators in a causal framework to the actual field situation.

The next step in the approach to environmental problems in estuaries is outlined in Figure 3 (63). The hierarchical diagram is used to scope the problem. Scoping the problem estimates possible perturbations on increasing spatial scales: a creek, a river-estuarine

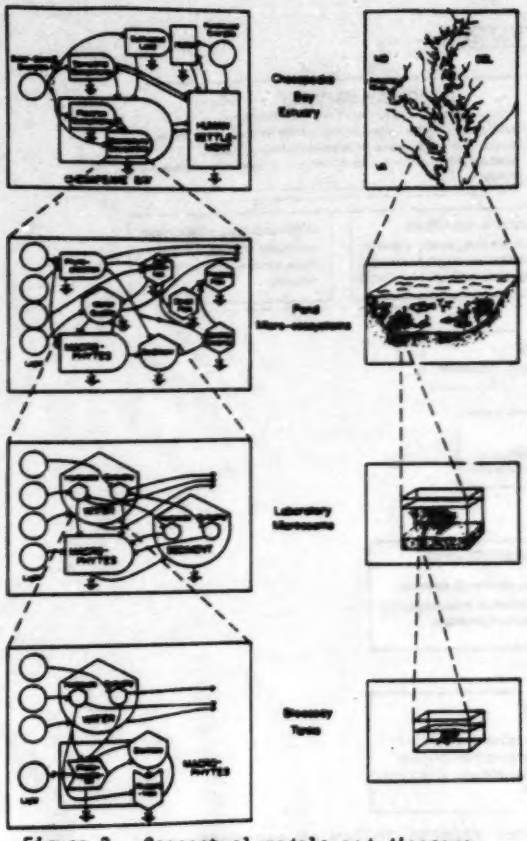

Figure 3. Conceptual models and diagrams showing the hierarchical nature of Chesapeake Bay as a regional system. Symbols used are from Odum (62). (From 63).

segment, a total estuarine system or open coastal waters. Examining the physical scale of the problem helps determine the next step in validation (47).

This next step involves estimation of whether chemical measurements or other endpoints used to represent pertubations can be measured within the scale of the question (e.g., creek, estuarine segment, etc.). This information helps define the appropriate subsystem (exposure field) in the hierachial structure that could be influenced by contamination or other pertubations. Absent, it is difficult to link effects to exposure under realistic conditions. In field experimental situations, where one has control over the exposure field, it is common practice to plan field exposures under predicted concentrations of a contaminant.

Once the problem has been scoped for potential considerations of realistic field exposure and the research question appears amenable to one or more enclosure experiments (i.e., laboratory and field corrals), then the mesocosm field enclosure/exclosure framework is applicable (Figure 4). Here, we see a gradation in experimental and ecological complexity from single-species to static microcosm tests through flow-thru microcosms to field mesocosms, to field enclosures/ exclosures and finally the full-field ecosystem. This experimental design allows for partitioning of extraneous variability in a reductionist sense and the ability to discern perturbation pathways in the system through which an effect may be propagated in a holistic context (20).

If the question is such that it is not feasible to use various kinds of experimental container systems, then the next best alternative is to attempt comparative ecological assessments, either employing beforeand-after baseline studies or comparative components of the field, i.e., matched embayments. This approach has an added advantage of increased ecological reality, but the possibility of not having a meaningful control or reference environment available may reduce the acceptability of the design. These alternative approaches with experimentation requirements are diagrammed in Figure 5. An effective long-term strategy would be to combine direct field experimentation with multiple references areas, similar to the approach employed in the York River estuary, Chesapeake Bay and Apalachicola Bay studies (6), with the expectation of increasing the

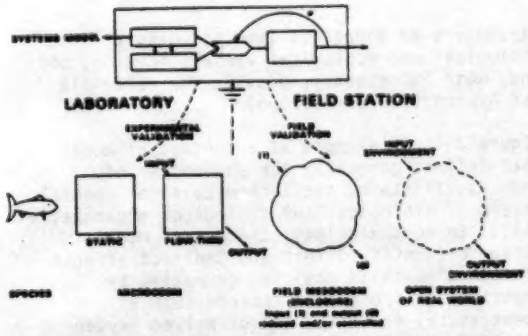

Figure 4. The key position of the field mesocosm (with controlled input (I), output (O), and systems model in the spectrum of study levels ranging from species to open systems of the real world (From 20).

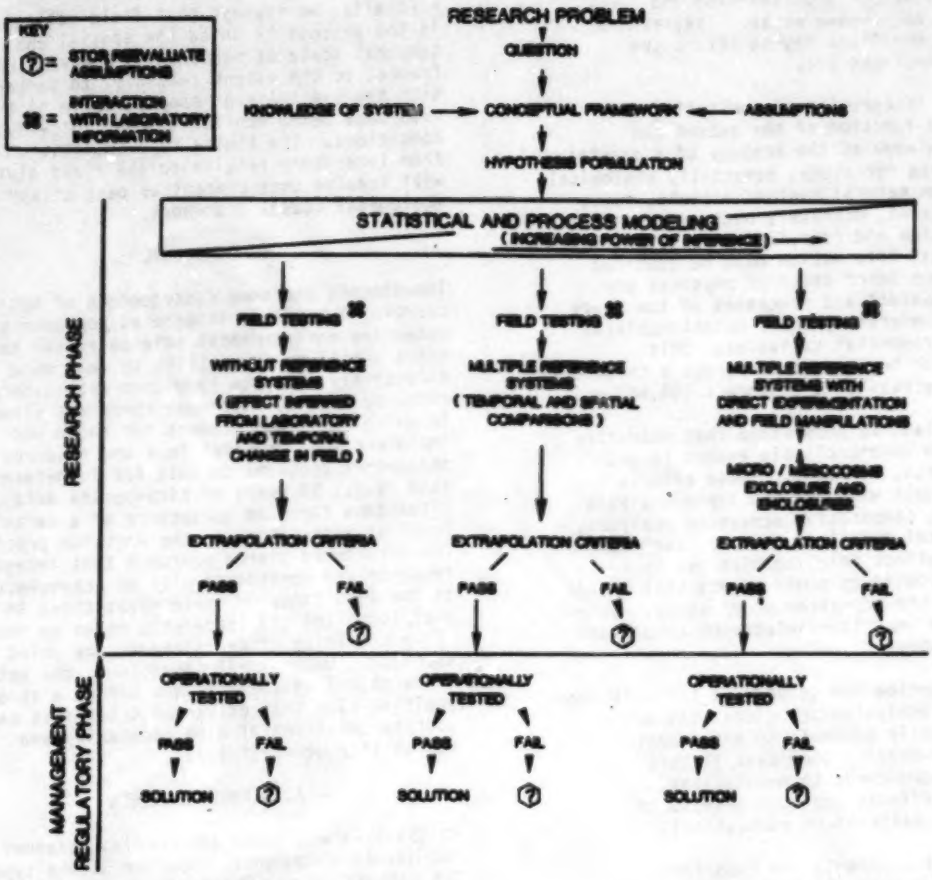

Figure 5. Conceptual organization for determining the limits of extrapolation of laboratory-derived information. Note the power of scientific understanding (reduction of uncertainity) increases from left to right. Management and regulatory operational "verification" is included to show the linkage between research and management.

power of generalization and predictability. The importance of transferring knowledge gained in the scientific phase to the management or regulatory phase to test if the management problem is properly conceived in a causal context is noted in Figure 5.

The strategy outlined herein has potential to test multiple hypotheses and generate complex data sets. Mathematical models are useful tools for quantifying ecological relationships and integrating data for gaining insights and making predictions. Statistical models can be used as a kind of exploratory dissecting kit or as tests of significance (53). However, process modeling with computer simulation can relate several interacting processes (64). Mann (65) gives some examples of that process models have provided ecological insights and useful predictions. He also discusses important limitations of such models, especially attempts to aggregate large numbers of complex variables.

Field validation incorporates a significant relationship between field monitoring and research. In our agency, recent emphasis on field validation is based upon predictability and generality of calibrated methods and models. We view this functionally as a fundamental form of inquiry.

5. SUMMARY

» Analysis of any environmental problem must begin with a clear statement of that problem followed by formulation of hypotheses that

relate to its deeper understanding and correction. Barnthouse et al. (29) remind us that some questions may be beyond the present state-of-the art.

• Success in integration of monitoring and research is a function of the extent and depth of knowledge of the ecology of a coastal area considered for study, especially biological information on natural history aspects, i.e., spawning patterns, migratory pathways, seasonality, predation and recruitment relationships. This biological information must be combined with a thorough description of physical and chemical parameters and processes of the study area to best understand their relationship(s) to these environmental variables. This information can be used to construct a conceptual model of the ecosystem of interest (55,56).

• It is important to understand that estuaries are subject to uncontrollable events (e.g., floods, droughts, El Nino). These effects can best be dealt with through trend analysis (time-series), comparative ecosystem analyses, and mathematical modeling; however, verification of cause-and effect relationships may be difficult following episodic events that change conditions of the ecosystem under study. Such changes become important antecedent conditions for future studies.

• One should decide how to address the influence of endogenous ecosystem processes that are not always readily amenable to experimental testing, e.g., density dependent factors that affect recruitment to populations, age-structure effects and edge effects of distributional patterns of populations.

• Environmental gradients are important ecologically and toxicologically and difficult to design into experimental systems at the appropriate scale.

• Important considerations in experimental design exist (see the ten principles outlined by Green [53]).

• Problems exist for which application of estuarine science is limited by inadequate theory. Only basic research and theoretical considerations of ecosystem behavior will improve problem definition and practical solution to problems.

• An analysis of scientific uncertainty is necessary to maintain a quality scientific program, but alone, it is insufficient for translating and synthesizing the meaning of scientific work for public understanding. The scientific community must contribute to the mutual educational process of how others view scientific uncertainties, because definition of uncertainties by themselves do not provide guidance on how they should be managed.

• Finally, we suggest that field validation is the process by which the spatial and temporal scale of research is hierarchically framed, to the extent feasible, to be congruent with the spatial and temporal scale of the phenomena being monitored under full-field conditions. The limits to extrapolation from laboratory results to the field always will involve this concept as part of any ecological causal framework.

6. CONCLUSION

Impediments and some consequences of not carrying out a more integrated approach to estuarine environmental science appear to exact a toll on our ability to deal more effectively over the long-term with estuarine resource issues. Although there are situations in which it is not prudent for those who implement environmental laws and resource management programs to wait for long-term data (e.g., 10 years of time-series data), such situations force an acceptance of a certain level of uncertainty in the decision process. The structured tiered approach that integrates research and monitoring with an acknowledgement of the importance of scale gives those in decisionmaking and leadership roles an indication of uncertainity of decisions at any point in the approach. Under ideal conditions, the entire hierarchical system approach offers a strong positive sign that estuarine scientists can address questions of high complexity and variability meaningfully.

7. ACKNOWLEDGMENTS

We thank Gerald Walsh and Charles McKenney for valuable comments. Maureen Stubbs typed the manuscript and Steve Foss and Lee Anne Newkirk provided graphics.

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